

# Effect of the Dip and Excavation Orientation on Roof Stability in Moderately Dipping Stone Mine Workings

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**ABSTRACT:** Underground limestone mines typically use the room-and-pillar method of mining in the generally flat-lying limestone formations. In some cases the dip may exceed  $5^\circ$  which can result in unique roof instability problems. Stability may be further exacerbated by the presence of horizontal tectonic stresses. Field studies and numerical model analyses are combined to assess the affect of the dip in various stress conditions. The results showed that where the horizontal tectonic stresses are sufficient to cause intact rock failure, increasing dip results in increased failure potential. The effect of the dip is greater when the maximum horizontal stress is parallel to the dip. Two case studies are presented and evaluated against the findings of stress analysis results. The study showed that the empirical rules of orienting headings parallel to the maximum stress are generally applicable to dipping excavations, except when mining in the up-dip direction. The importance of accurately determining the orientation of the maximum horizontal stress is emphasized because the window of favorable orientations relative to the stress is small.

## 1. BACKGROUND

There are 118 operating underground stone mines listed in the Mine Safety and Health Administration's list of stone mine workings [1]. All of these mines may not be operational at any particular point in time. The mines generally use room and pillar methods to extract limestone formations at depths of cover that range from outcrop to approximately 900 m (3,000 ft). About 80% of the mines operate at a depth of cover of less than 90 m (300 ft). The formations are usually flat dipping, but some mines that are located along synclinal or anticlinal structures can operate at moderate dips of between  $5^\circ$  and  $20^\circ$ . A few cases exist where mines operate at dips of between  $20^\circ$  and  $90^\circ$ .

### 1.1. Horizontal Stress

Horizontal tectonic stresses have been identified as one of the causes of roof instability in stone mines [2] and can be associated with microseismic activity [3]. The mines are located in the mid-North American plate where elevated horizontal stresses

have been measured [2] in the limestone formations and in many of the area's coal mines [4]. Latest research has shown that the horizontal stress may be explained by the effect of plate tectonics [5, 6]. Tectonic loading is related to the movement of the North American plate as it is pushed away from the mid-Atlantic ridge. Elevated stresses are not necessarily present in all the limestone formations because local features such as outcropping and folding may have relieved the stresses over geological time [7]. The tectonic stresses can cause roof failure by progressive shearing of rock beams in the roof of the excavations. Failure of the intact rock has been observed in dipping excavations, where tectonic stresses were present [8].

In lower stress environments the dip of the workings can also affect the stability of the roof beam by mobilizing shearing along specific joint sets, without failing the intact rock. Failure in low stress conditions is characterized by movement of large blocks that are bounded by joint surfaces.

### 1.2. Mine Layout

Experience has shown that poor roof conditions can be mitigated by changing the mine layout so that the rooms and pillars are aligned more favorably to the prevailing field stress and local joint orientations, [2, 4, 9, 10]. An example of the successful re-orientation of stone mine workings is presented in Kuhnhein and Ramer [11]. In general, the empirical guidelines advocate aligning the direction of heading advance parallel to the direction of the maximum horizontal stress. The experience and empirical guidelines for optimizing layouts are, however, largely based on mining in near horizontal formations.

At moderate dips it is not always possible to orient the mining layout in the most favorable direction for rock stability. The direction of the workings can be dictated by the operational requirements of a relatively shallow dipping floor for the large rubber wheeled mining and hauling equipment. One solution to the problem is to develop the headings and cross-cuts at an inclination to the strike of the formation, providing access at a more favorable “apparent dip”. This orientation may not be the most favorable for rock stability.

### 1.3. Objectives

In the case of a dipping formation, the complex interactions between the dip and the field stress, joint orientations and mine geometry are not readily apparent, making it difficult to design a mine layout that optimizes roof stability. This paper presents the results of numerical model studies and field observations that were carried out in an investigation of the effect of the dip on roof stability. The study was limited to cases where the field stresses are sufficiently large to affect roof stability. An additional objective was to determine whether the empirical guidelines for layout design in flat dipping formations are also applicable to room and pillar workings at moderate dips.

## 2. FIELD OBSERVATIONS OF DIP EFFECTS ON ROOF STABILITY

Two underground stone mines in the Northern Appalachian region have been studied as examples of the effects of dip on roof stability. The mine layouts, observed failures and the issues related to roof stability in dipping formations are discussed below.

### 2.1. Case Study 1: A mine in the Loyalhanna Limestone Formation

The mine extracts high quality limestone for construction purposes from the Loyalhanna Limestone Formation in the Chestnut Ridge area, Western Pennsylvania. The workings located on an anticlinal structure and are nearly horizontal along the crest of the anticline but the dip increases to  $7^\circ$  in the south-western part of the mine as the mine expands down the side of the anticline. The Rock Mass Rating (RMR) [12] of the Loyalhanna limestone is in the range of 85 to 90 units.

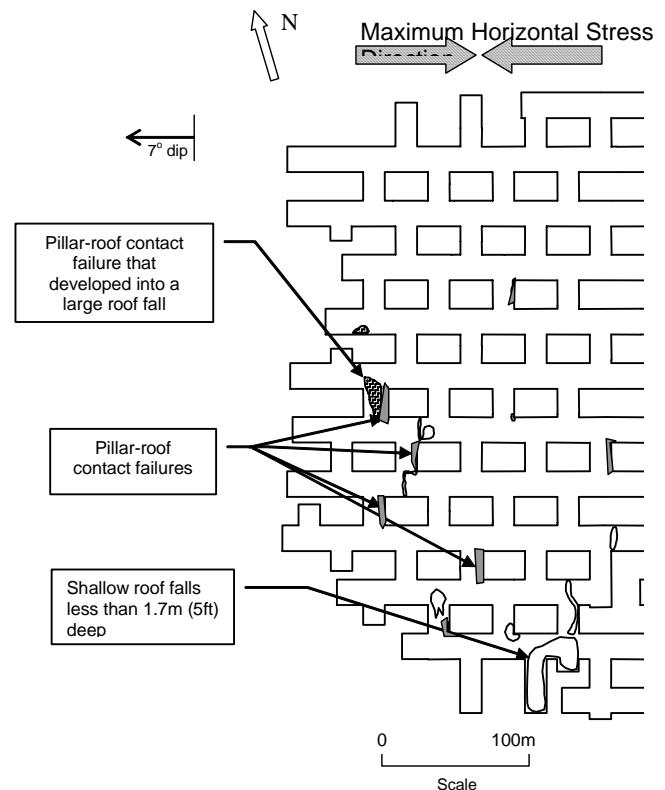


Fig. 1. Sketch plan of Case Study 1 showing mine layout, location of roof instability and direction of maximum stress.

The mine exhibits many of the characteristic signs of excessive horizontal stress conditions. Mapping of roof damage has confirmed the presence of sporadic roof shearing and occasional massive directional roof falls. In addition, asymmetrical failures at the pillar-roof contact were observed only in the southwestern part of the mine where the dip is gradually increasing. Figure 1 shows a plan view of a portion of the workings and the locations of pillar-roof contact failures as well as other roof failures. One of the failure areas progressed into a major directional fall, with a result that the entire area had to be abandoned because of safety concerns. Figure 2 shows a roof collapse that was initiated by failure at the pillar-roof contact. Based

on stress mapping and numerical modeling of the failures, it was concluded that the major horizontal stress was parallel to the dip of the workings in the area. An analysis of the effect of the dip on roof stability in this case [8] showed that the high tectonic stresses were concentrated in the up-dip corner of the rooms and could explain the observed failures. However, the study did not assess the optimal direction of the workings relative to the dip and the high field stresses.



Fig. 2. Roof failure at Case Study 1, view looking down dip.

## 2.2. Case Study 2: A Mine in the Linden Hall Formation

The second case study mine extracts the Valentine Limestone Member along the Nittany syncline within the Linden Hall Formation, in Central Pennsylvania. The Valentine member is about 25 m (80 ft) thick and dips at 10 to 15° to the south-east. The mine extracts approximately 8 m (25 ft) of the limestone by initial development followed by benching operations to a height of about 20 m (65 ft). Rooms are 15m (50 ft) wide. The heading and cross-cut directions of the workings were laid out so that the floor dips at an apparent inclination of 5-10% for operational reasons. As a result, the headings and cross cuts are approximately 30° off-strike. The rock mass rating (RMR) [12] is between 57 and 69 in the areas where roof failures were observed. Two prominent, steeply dipping joint sets exist within the rock mass that strike at N57°E and N33°W. The joint sets are respectively parallel to the strike and dip of the formation. Less well developed, shallower dipping joints were also observed in the rock mass.

Various types of roof failure were observed in the mine. In the shallower areas, typical joint delineated failure was observed, in the absence of significant

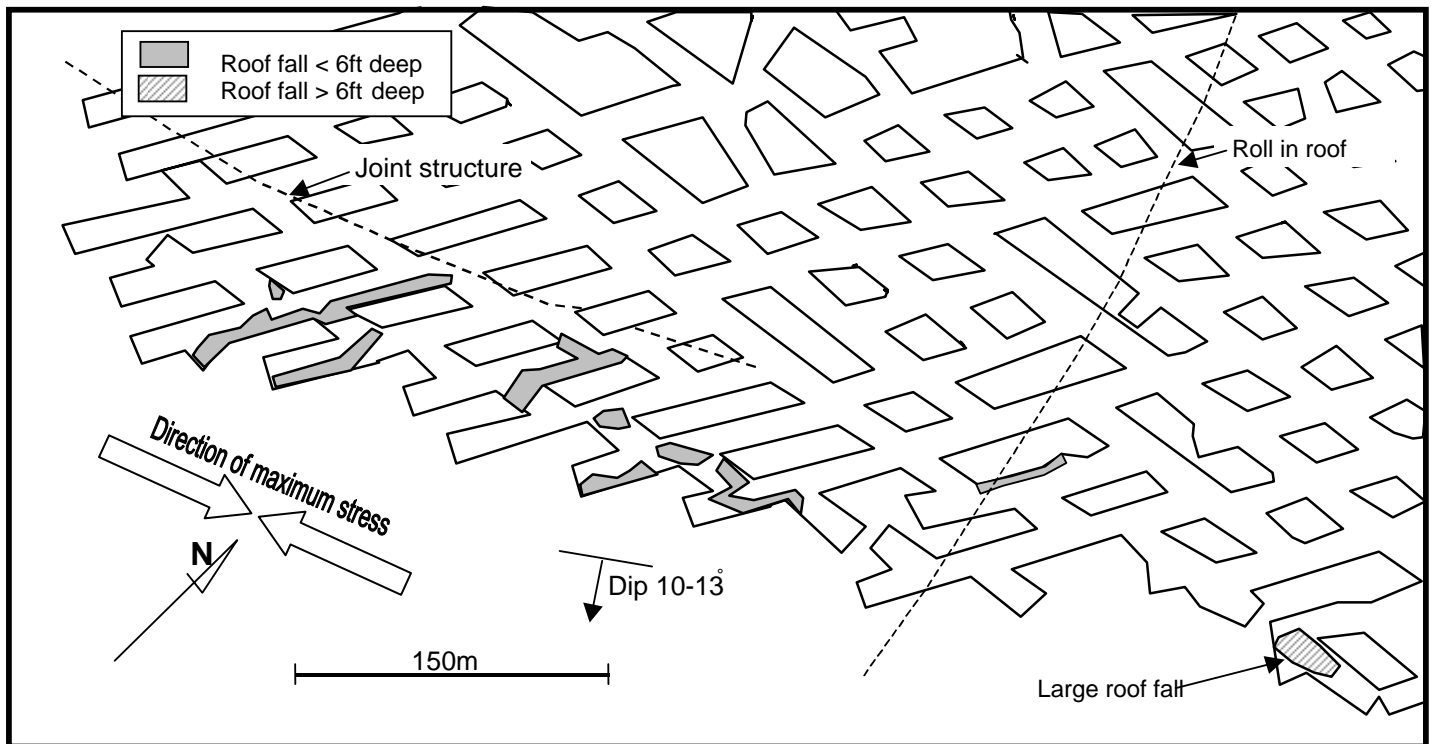


Figure 3 : Sketch plan of case study site 2 showing room and pillar layout, location of roof instability and orientation of maximum horizontal stress

field stresses. As the depth of cover increases, signs of stress related failure was observed. The mine layout and the location of the observed roof failures in the deeper part of the mine are shown in figure 3, where the depth of cover is between 150 and 240 m (500-800 ft). Failure of the intact rock at the pillar-roof contact was observed at the up-dip side of one of the rooms, while failure along the down dip side was observed in five of the headings. Some of the failures ran across the rooms. Figure 4 shows a typical roof failure that occurred along the down dip side of the headings. The local jointing appeared to have contributed to the failure of the immediate roof beam in some of these headings. A large scale collapse in one of the intersections at the deepest part of the mine, also shown in figure 3, was a further confirmation of the presence of horizontal tectonic stresses. At this location the failure mode was similar to that described by Iannacchione et al. [7], having an elliptical shape with shear rupturing of the roof beds. Stress mapping [4] was conducted, which indicated that the maximum horizontal stress is oriented approximately along the strike of the workings, at N70°E, this coincides with the regional tectonic stress in North-Eastern Pennsylvania [5].

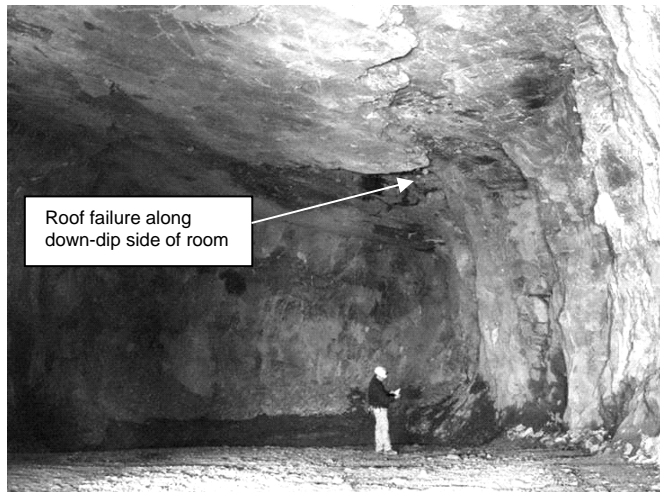


Fig. 4. Roof failure in heading at Case Study 2.

The occurrence of asymmetrical roof failures indicated that the dip of the workings had an effect of the mode and severity of roof failure. The presence of increasing tectonic stresses with increasing depth was a further complicating factor in this case.

### 3. ANALYSIS OF DIP EFFECTS ON ROOF STABILITY

Three-dimensional numerical stress analyses were carried out to evaluate various combinations of excavation layouts, formation dips and stress conditions. The analyses were all based on the assumption that a relatively high tectonic stress is present in the limestone formation, which can initiate failure of the rock mass within the roof of the workings. Shearing along individual joints was not considered, but rather general rock mass failure in response to excessive stresses. In practice, roof stability can also be affected by individual joints or other structures, which were not included in these analyses.

#### 3.1. Modeling Method

The FLAC3D finite difference code [13] was used to conduct the analyses. Several models were set up to simulate arrays of rooms and pillars, an example of one of the models is presented in Figure 5, which shows the element sizes used to model the pillars, roof and floor rocks. The basic layout simulated a grid of square pillars 15 x 15 m wide by 10 m high. The rooms were also 15 m wide, resulting in a typical 75% extraction. The excavations were all assumed to be located in a uniform, elastic rock mass.

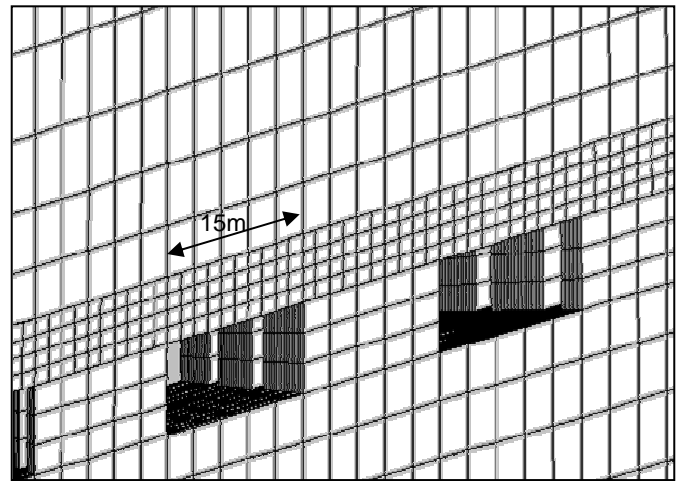


Figure 5: Cut-away view of a three-dimensional model of a room and pillar layout, showing element sizes in the pillars, the roof and floor rocks.

The models were loaded by field stresses of 5 MPa in the vertical direction to simulate overburden of 100 m. The horizontal stresses were set at 20 MPa and 10 MPa to simulate a typical tectonic stress field. The direction of the maximum horizontal was varied in the analyses. The effect of the dip was assessed by tilting the models through 10°, 15° and

20° while maintaining the stresses in their original orientations.

The relative merits of the different layouts were evaluated by comparing the volume of potential roof failure. The failure volume was calculated by the Coulomb criterion, using a cohesion value of 12 MPa and a friction angle of 30°. A “stability index” was calculated, which is the ratio of rock strength to the maximum stress, this is similar to a safety factor. Contours of the stability index provide a good visual impression of the extent and location of potential roof failures.

### 3.2. Effect of the Dip on Roof Stability

Two cases were considered, in the first case the maximum horizontal stress was set parallel to the dip of the formation, similar to Case Study 1, and in the second the maximum horizontal stress was parallel to the strike, similar to Case Study 2. The effect of the dip on roof stability was evaluated by calculating the failure volume in the central part of the array of rooms and pillars, so that edge effects would not be included. Figure 6 summarizes the results, which show that an increasing dip can have a significant effect on roof stability if the major horizontal stress is parallel to the dip of the workings. However, if the maximum horizontal stress is parallel to the strike, the formation dip has only a limited effect on roof stability. Figures 7 and 8 show the stability index 2 m above the roof of the workings for a dip of 0 and 15°, respectively. It can be seen that the increased dip causes a greater amount of failure in the roof between pillars, note that the intersections are not as severely affected as the rooms.

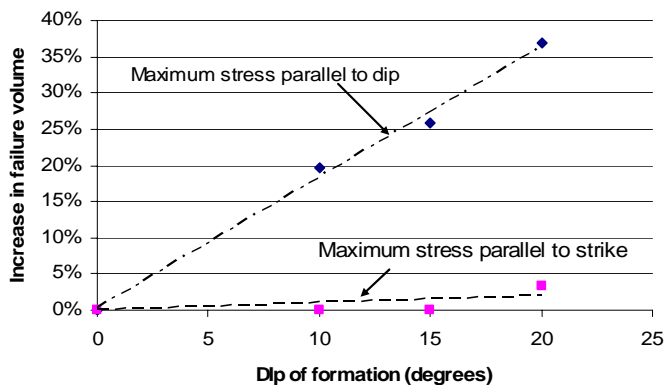


Fig. 6. Effect of dip on volume of failure in the roof of room and pillar workings.

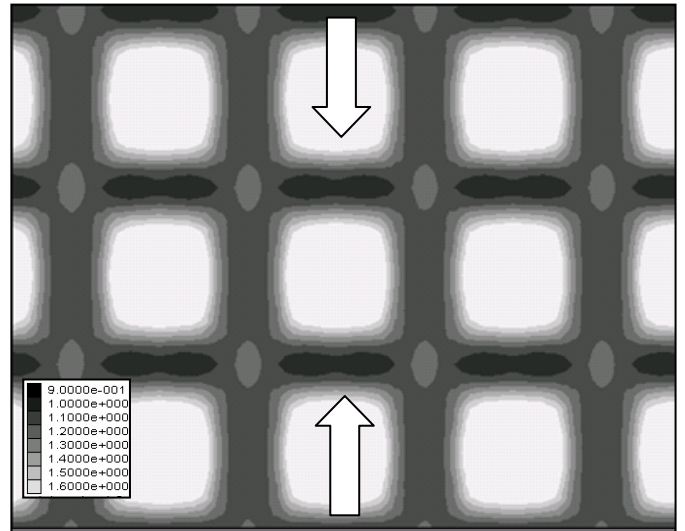


Fig. 7. Plan view showing failure index contours in immediate roof of horizontal workings, maximum horizontal stress direction shown by the arrows

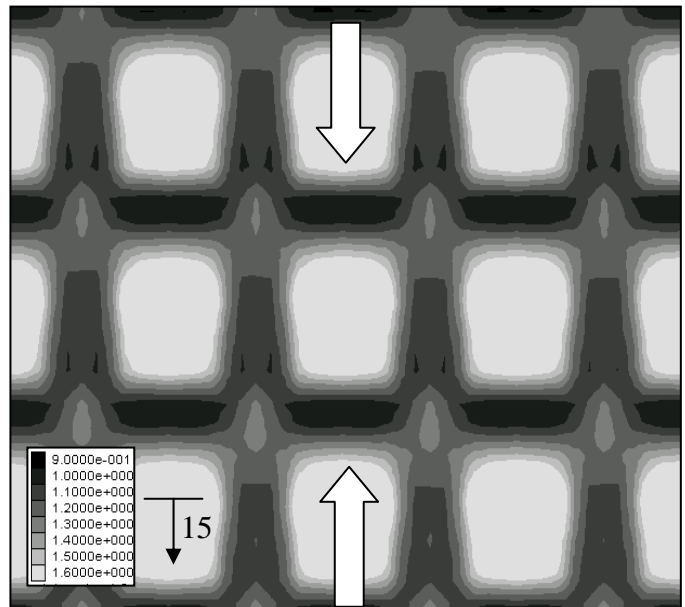


Fig. 8. Plan view showing failure index contours in immediate roof of workings dipping at 15°, maximum horizontal stress direction shown by the arrows.

### 3.3. Effect of Heading Orientation on Roof Stability

A second set of analyses was carried out in which the effect of changing the orientation of the workings was assessed. The objective was to obtain insight into roof stability in cases where mines are forced to change the heading orientation to achieve a desired apparent dip. This evaluation was carried out by modeling a single heading at various orientations relative to the dip direction of the limestone formation. The same two stress conditions described above were evaluated. These analyses were all carried out at a dip of 15°. The results were evaluated by comparing the potential

failure volume in the roof within the first 10m behind the face. All the results were normalized to the failure volume for a heading that is parallel to the maximum horizontal stress.

The results for the case where the maximum horizontal stress is parallel to the strike of the formation are summarized in figure 9. Here it can be seen that a heading parallel to the maximum stress will experience the least amount of failure, as predicted by the empirical guidelines. However, a small deviation from this optimal direction causes a rapid increase in the potential roof failure, especially if the heading is advanced in the down-dip direction.

For the case where the maximum horizontal stress is parallel to the dip of the formation, the results are quite different, as shown in figure 10. Here it can be seen that the most favorable direction of advance is in the down dip direction ( $0^\circ$ ), which is also parallel to the maximum principal stress. Any deviation from this direction results in a rapid increase in the amount of potential failure. Advancing in the up-dip direction ( $180^\circ$ ) is shown to be relatively unfavorable because the horizontal stresses are concentrated at the top of the face and will cause damage to the roof rocks. When advancing down dip, the stresses will be concentrated in the floor, while the roof remains relatively unaffected.

#### 4. APPLICATION OF RESULTS TO CASE STUDIES

The above results can be used to comment on the stress effects on roof stability at the two case study mines. The discussion only addresses failure induced by the horizontal tectonic stresses. Other issues such as joint directions and other geological structures are specifically excluded here, but would have to be considered when deciding on alternative layouts.

##### 4.1. *Discussion of Case Study 1*

Based on the results of the numerical model analyses, the current down-dip direction of advance appears to be the most favorable orientation for the workings, given that the maximum horizontal stress is parallel to the dip direction, refer to figure 10. However the results in Figure 6 show that the increasing dip can result in increasing roof instability.

##### 4.2. *Discussion of Case Study 2*

The headings at Case Study 2 are developed  $30^\circ$  off-strike and the maximum horizontal stress is nearly on strike. Based on the results in figure 9 it can be seen that these orientation are unfavorable for stress induced failures and the stress field can be one of the causes of roof instability. The requirement to mine at an apparent dip has indirectly contributed to the roof instability at this mine.

#### 5. SUMMARY AND CONCLUSIONS

The findings of this study relate to room and pillar type stone mining excavations in a highly anisotropic stress field, with the major principal stress being horizontal. The stresses were assumed to be sufficiently large to initiate failure of the rock mass in the roof of the excavations. Under these conditions, the study showed that:

- An increase in the dip of the workings will cause an increase in roof instability, especially when the maximum horizontal stress is aligned in the dip direction of the workings.
- The most favorable direction for heading advance is parallel to the orientation of the maximum horizontal stress, except when the advance is in the up-dip direction.
- The range of favorable orientations is narrow; a deviation of  $30^\circ$  from the optimum direction can be just as bad as being  $90^\circ$  off.
- The empirical guidelines, advocating heading development parallel to the direction of the maximum horizontal stress are also applicable in dipping formations, except when advancing in the up-dip direction.

The study has shown that the dip combined with elevated tectonic stresses can have a detrimental effect on the stability of stone mine workings, as seen at the two case study mines. The results of the numerical model analyses reported above can be used to assist in orienting mine workings relative to the stress field in dipping workings. The importance of accurately determining the orientation of the maximum horizontal stress by stress mapping or direct measurement is emphasized, because the window of favorable orientations relative to the maximum stress direction is small.



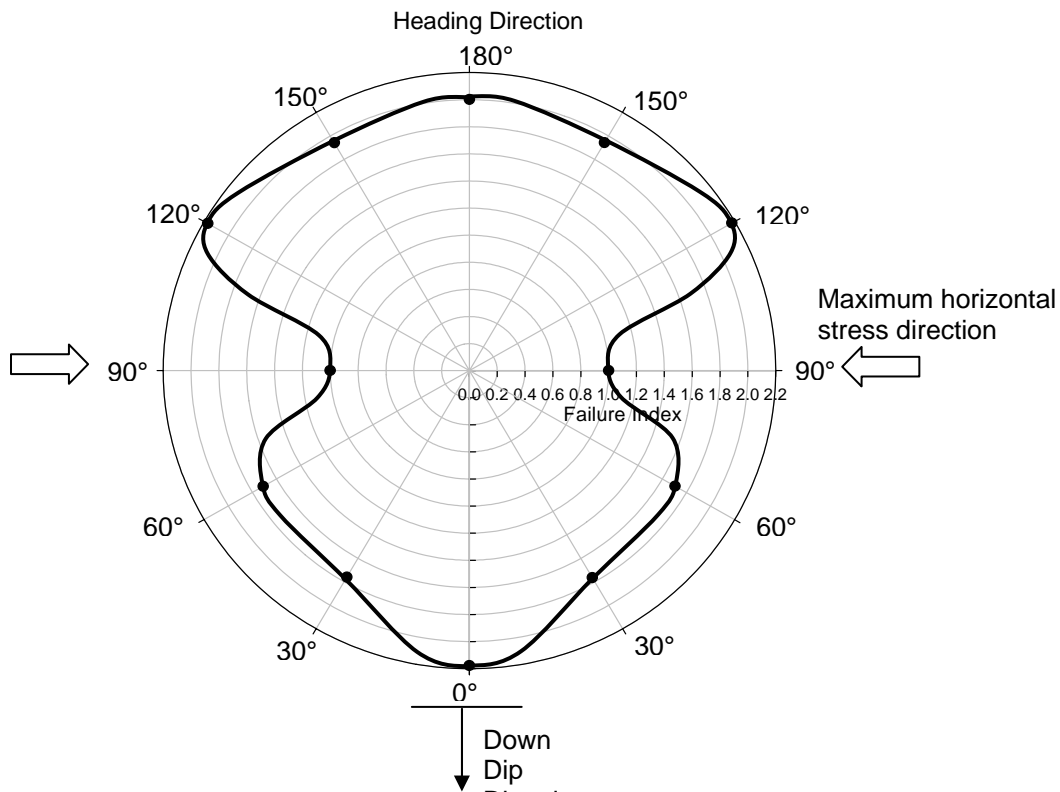


Figure 9: Roof failure index versus heading advance direction. Maximum horizontal stress is parallel to the *strike* of the formation. The formation dip is 15°. Increasing failure index indicates increased failure potential.

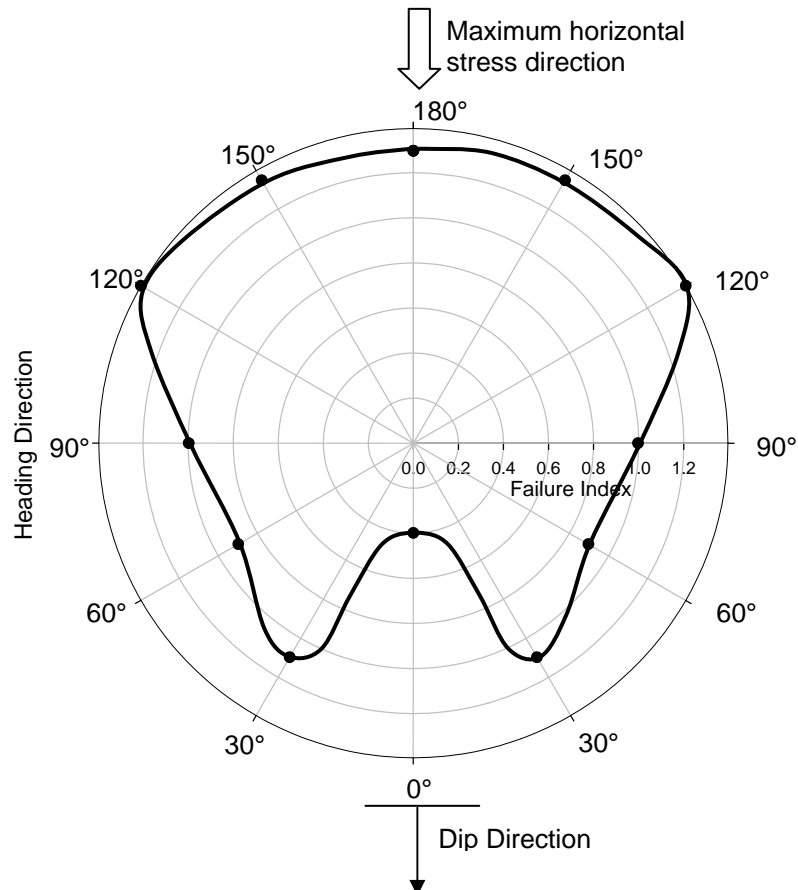


Figure 10: Roof failure index versus heading advance direction relative to the dip. Maximum horizontal stress is parallel to the *dip* of the formation. The formation dip is 15°. Increasing failure index indicates increased failure potential.

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